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The following problems were studies during the course of the research:

i) Routing and optimal scheduling in communication networks.
ii) Optimal scheduling of failure prone flexible manufacturing systems.
iii) Determining when zero-inventory policies are optimal.
iv) Characterizing worst-case strategies in sequential decision problems.
v) Determining minimum variance control laws for general multi-variable ARMAX systems.

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vi) Determining the necessary and sufficient condition for simulated annealing to hit the global minimum with probability one.

vii) Developing stable distributed, real-time scheduling algorithms for large flexible manufacturing/assembly/disassembly systems.

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Final Report on Contract No. DAAG-29-85-K-0094

ARO Proposal No.: 22260-MA
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Principal Investigator: Professor P. R. Kumar

I. Statement of Problems Studied

We have examined the following problems:

i) Routing and optimal scheduling in communication networks;

ii) Optimal scheduling of failure prone flexible manufacturing systems;

iii) Determining when zero-inventory policies are optimal;

iv) Characterizing worst-case strategies in sequential decision problems,

v) Determining minimum variance control laws for general multi-variable ARMAX systems.

vi) Determining the necessary and sufficient condition for simulated annealing to hit the global minimum with probability one, and

vii) Developing stable distributed, real-time scheduling algorithms for large flexible manufacturing/assembly/disassembly systems.

II. Summary of the Most Important Results

i) A central problem in communication networks is that of choosing the routes which the individual packets must follow in order to reach their destination from the origin. Though fixed routes can be established for each origin - destination pair, such policies are static and their performance can be improved by **dynamic** policies which choose routes on the basis of the existing traffic and network state. We have examined a particular case of the dynamic routing problem where one has to choose between several parallel routes, each of possibly different speed. We have shown that in some cases, systemwide optimal routing policies are also user optimal, and that further, such user optimal policies are **insensitive** to the probabilistic nature of the arriving traffic. In the particular case of exponentially distributed rout traversal times, the optimal policies are simply given by certain trivially computable threshold numbers.

ii) A critical problem in the scheduling of flexible manufacturing systems is to take optimal advantage of their flexibility and easy reconfigurability. We have examined the particular case of obtaining scheduling policies which maintain the production rate at a desired level inspite of inevitable machine failures. We have shown that there exists an **Optimal Inventory Level** and production must be always maintained so that this Optimal Inventory Level is reached as rapidly as possible. The optimal policies are thus of bang-bang type. Moreover, the optimal inventory level is trivially computable.

iii) We have examined the general problem of increasing the productivity of manufacturing systems. As well known, **inventory levels** are a key component of the cost of manufacturing. Recent developments in Japan dealing with the concept of **zero-inventory manufacturing** have attracted much attention in the U.S. This idea, linked to such concepts as the Kan-Ban system, and stockless production, are being emulated bv manufacturers in this country. A fundamental question in this regard is whether zero-inventory policiers can ever be optimal for a manufacturing system, or whether they are implemented merely to enforce greater discipline on the manufacturing process.

We have considered the problem of controlling the production rate of a failure prone manufacturing system in an optimal way. In the case of an average cost criterion we have determined conditions under which a **zero inventory level** is optimal. This gives a mathematical basis and a rigorous proof of optimality of a class of policies known as **zero inventory policies** and the concept of **stockless production.**

It should be kept in mind that *zero-inventory* policies and *stockless production* are at the center of a virtual revolution in manufacturing systems. Ours is a surprising result which shows that such zero-inventory policies can actually be optimal even in the presence of uncertainty.

iv) We have examined the problem of characterizing worst case strategies in sequential decision problems. The result obtained is that these strategies can be obtained by dynamic programming algorithms even when a saddle point does not exist.

v) We have determined minimum variance control laws for general multivariable ARMAX systems. This determination was known earlier to be a difficult problem when the system has a general delay structure or is of nonminimum phase. We have overcome both difficulties.

vi) A problem central to a vast number of applications in communication networks, computer systems, manufacturing systems, operations research and other fields is the problem of combinatorial optimization. Here one needs to obtain the minimum of a cost function over several allowed configurations of the system. Usual descent algorithms get trapped in local minima. To overcome this, a new scheme called **simulated annealing** has been introduced. This scheme takes random uphill moves, with the randomness described by a parameter called **temperature**, in analogy with the physical annealing process (where nature attains the lowest energy crystalline configuration when an object is cooled slowly).

We have studied the problem of the critical rate of cooling needed to guarantee that simulated annealing will lead to a global, as opposed to local minimum. The underlying question deals with the asymptotic properties of a time-inhomogeneous Markov chain reminiscent of the singularly perturbed type, but with small parameter (the temperature) converging to zero. We have developed a new theory for such processes, which utilizes a new notion of **balance of recurrence order**. This theory, as a special case, allows us to determine the necessary and sufficient conditions for simulated annealing to hit a global minimum with probability one. It also allows us to determine the rates of convergence involved. We believe that this is a very fundamental theoretical breakthrough for the analysis of the general class of such time-inhomogeneous Markov processes.

vii) We have obtained some significant results on the problem of **real-time scheduling** of Flexible Manufacturing Systems.

Most of the literature of the past few decades has concentrated on formulating scheduling problems as mixed integer programming problems. The solution of these problems is quite hopeless for reasonably sized systems, since the complexity of the procedures grows exponentially in the number of machines, parts and time horizon. Hence these procedures could not really be implemented in real-time.

By adopting a totally new approach we have been able to develop **stable, distributed real-time scheduling algorithms for very general flexible manufacturing/assembly/disassembly systems of arbitrarily larger size.**

Our algorithms can handle various real world complexities such as multiple part-types, set-up times. rerouting due to yield, and transportation delays.

Our class of scheduling policies are trivial to implement in real-time and ensure that the cumulative production of each part type trails the desired production by no more than a constant. We also exhibit an upper bound on the backlog, as well as explicit lower bounds on the performance of **any** algorithm. We are very enthusiastic about this new approach and believe that it has enormous potential.

III. List of Participating Scientific Personnel

i) Professor P. R. Kumar, Principal Investigator.

ii) Daniel P. Connors; Graduate Research Assistant obtained Ph.D. while partially supported by contract. **Thesis Title:** Balance of Recurrence Orders in Time-Inhomogeneous Markov Chains with Application to Simulated Annealing.

iii) Sheng-Fuu Lin, Graduate Research Assistant.

IV. List of Publications

1. P. R. Kumar and J. Walrand, "Individually Optimal Routing in Parallel Systems," *Journal of Applied Probability*, vol. 22, pp. 989-995, December 1985.
2. R. Akella and P. R. Kumar, "Optimal Control of Production Rate in a Failure Prone Manufacturing System," *IEEE Transactions on Automatic Control*, pp. 116-126, vol. AC-31, No. 2., February 1986.
3. R. Akella and P. R. Kumar, "Optimal Control of a Failure Prone Manufacturing System," *Proceedings of the 24th IEEE Conference on Decision and Control,*" p. 1693, Fort Lauderdale, FL, December 11-13, 1985.
4. T. Basar and P. R. Kumar, "On Worst Case Design Strategies," *Computers and Mathematics with Applications : Special Issue on Pursuit - Evasion Differential Games, (Invited Paper)*, vol. 13, No. 1-3, pp. 239-245, 1987.
5. R. Akella and P. R. Kumar, "Optimal Scheduling of a Flexible Manufacturing System : A Stochastic Control Problem for a System with Jump Markov Disturbances,"

pp. 131-134, *Computational and Combinatorial Methods in Systems Theory*, Editors: C. Byrnes and A. Lindquist, North Holland, 1986. (*Proceedings of MTNS-1985 - 7th International Symposium on the Mathematical Theory of Networks and Systems, Stockholm, June 10-14, 1985.*)

6. U. Shaked and P. R. Kumar, "Minimum Variance Control of Discrete Time Multivariable ARMAX Systems," *SIAM Journal on Control and Optimization*. vol. 24, no. 3, pp. 396-411, May 1986.

7. T. Basar and P. R. Kumar, "On Worst Case Design Strategies," pp. 64 - 65, *Proceedings of Optimization Days 1986*, Montreal, Canada, April 30 - May 2, 1986.

8. T. Bielecki and P. R. Kumar, "Necessary and Sufficient Conditions for a Zero Inventory Policy to be Optimal in an Unreliable Manufacturing System," *Invited Paper*, in *Proceedings of the 25-th IEEE Conference on Decision and Control*, pp. 248-250, Athens, Greece, Dec. 10-12, 1986.

9. T. Bielecki and P. R. Kumar, "Optimality of Zero Inventory Policies for Unreliable Manufacturing Systems", to appear in *Operations Research.*

10. D. P. Connors and P. R. Kumar, "Balance of Recurrence Order in Time-Inhomogeneous Markov Chains With Application to Simulated Annealing," to appear in *Probability in the Engineering and Informational Sciences*, vol. 2, pp. 157-184, 1988.

11. P. R. Kumar and T. Bielecki, "Optimality Inventory Levels for an Unreliable Manufacturing System: Necessary and Sufficient Conditions for a Zero Inventory Policies to be Optimal," pp. 158-159, vol. 4, *Proceedings of the 10th IFAC World Conference on Automatic Control*, Munich, W. Germany, July 27-31, 1987.

12. D. P. Connors and P. R. Kumar, "Simulated Annealing and Balance of Recurrence Order in Time-Inhomogeneous Markov Chains," pp. 1653-1656, vol. 3, *Proceedings of the 26th IEEE Conference in Decision and Control*, Los Angeles, Dec. 9-11, 1987. (Invited Paper).

13. J. Perkins and P. R. Kumar, "Stable Distributed Real-Time Scheduling of Flexible Manufacturing/Assembly/Disassembly Systems," submitted to *IEEE Transactions on Automatic Control*, December 4, 1987.

14. D. P. Connors and P. R. Kumar, "Simulated Annealing and Balance of Recurrence Order in Time-Inhomogeneous Markov Chains," p. 66, *Proceedings of the Indo-US Workshop on Systems and Signal Processing*, Bangalore, India, Jan. 8-12, 1988. (Invited Paper).